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UNPUBLISHED PRELIMINARY DATA (NASA Grant NsG-330)

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N64 13929*

[1963] 35p. refs

CODE-1

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This is the manuscript of a talk Presented ~~by A. Javan on November 5, 1963~~ at the Materials Science Colloq~~uium at Cornell University~~, Ithaca, N~~ew York~~, 5 Nov. 1963 Submitted for Publication

OTS PRICE

XEROX	$ 3.60 ph.
MICROFILM	$ 1.25 mf.

C.A. Massachusetts Inst. of Tech., Cambridge

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Gaseous Optical Masers and Their Applications*

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Introduction

A gaseous discharge is generally a non-thermodynamical system. The population distribution within the excited atoms in the discharge depends on the energy distribution of the electrons, the lifetimes of the excited atomic states and their modes of excitations by atomic or electronic impacts.

In the absence of thermodynamical equilibrium, a pair of excited atomic (or molecular) levels may exhibit a state of population inversion in which the density of the atoms in the more energetic level may exceed that of the lower energy level.[(1),(2)] If an optical transition is allowed between such a pair of levels, the process of stimulated emission of radiation will then lead to amplification of an incident electromagnetic radiation at frequencies within the line width of this transition,[(3)] (Fig. 1). Thus, a gaseous discharge tube containing an appropriately chosen gas, once excited by means of an external electrical power, may constitute a simple light amplifier at a number of discreet frequencies corresponding to transitions within the pairs of levels exhibiting population inversion.

With a light amplifier at hand, a light oscillator may be realized by introducing positive feed back in the amplifier. This is generally done by placing the discharge tube within an optical resonator consisting of two plane parallel or two spherical mirrors. Multiple reflections of light between the two mirrors through the amplifying medium will render the system unstable if the gain of the medium exceeds the loss of power upon each reflection from the end mirrors. In practice, dielectrically coated mirrors provide highest reflection coefficients. These mirrors, at best, have a reflection coefficient of about 99% leading to a loss of about one per cent of power upon each reflection. Thus, the amplifying medium is required to present at least a gain of about one per cent in order to satisfy the requirement for the oscillation threshold. Once this requirement is satisfied and the mirrors are aligned, a steady state oscillation will be established leading to extremely monochromatic and well defined oscillation at an optical frequency. We shall discuss later below that, in actual practice, using a He-Ne gaseous discharge optical maser,[4], a frequency purity[5] better than 8 parts in 10^{14} has been achieved at a frequency of 2.6×10^{14} cycles/sec. corresponding to a wavelength of 1.15μ. The major source of long term frequency drift is due to thermal effects. In an actual case, this drift has been reduced to a few cycles per second per second. For a given maser, over long periods of time, a frequency resetability as good as 0.5 megacycles per second, or about one part in 10^9, has been obtained. The latter quantity gives the degree of definition of the oscillation frequency which is important in connection with applications of the device as standard of length to be discussed later.

He-Ne System

This system is capable of producing oscillations at a large number of wavelengths.[(1),(2),(4),(6),(7),(8)] Its range now covers a number of transitions in the red-yellow region of the spectrum as well as numerous transitions in the infrared region.

The Ne atoms are responsible for the atomic transitions leading to maser oscillations. The He atoms provide a highly efficient source of excitation of the maser levels of Ne. Fig. 2 gives the diagrams of the relevant energy levels of the excited states of the Ne and He atoms. The maser levels of Ne are grouped in sets of either four or ten close lying energy levels. The groups consisting of four levels, in Paschen notations, are the (2s) and (3s) groups and those consisting of the set of ten levels are the (2p) and the (3p) groups of levels. While the (2p) and the (3p) levels are short lived due to their rapid rates of radiative decays, the (2s) and (3s) levels are comparitively long lived and possess lower rates of radiative decays. In a discharge consisting of about one mmHg of He and 0.1 mmHg of Ne, the (2s) and the (3s) levels are densely populated due to their long average life times and their particular modes of excitations involving collisions of Ne atoms with He metastables, to be described below. The short lived (2p) and (3p) levels, however, are comparitively less dense. Thus, the populations of the (2s) group of levels are inverted with respect to the (2p) levels, while those of the (3s) levels are inverted with respect to both of the (3p) and the (2p) levels.

The energy of the He (2^3S) metastable is near resonance with the excitation energy of the (2s) levels of Ne. A two body collision involving a He (2^3S) and a Ne atom in its ground state results in a transfer of excitation in which the He (2^3S) decays to the ground state while the Ne atom is simultaneously excited into one of the 2s levels. Similarly, the (3s) levels of Ne are produced primarily by excitation transfer from the He (2^1S) having an energy near resonance with the energies of the (3s) levels of Ne.

The above mode of excitation of the Ne atoms is highly selective and efficient. The effective cross sections of excitations of the two He metastables by collisions between electrons and the He ground state atoms, are particularly large. This results in a large rate of productions of the He metastables in a He-Ne mixture. Once a He metastable is produced, it will decay essentially by colliding with a Ne atom and hence exciting it into either one of the (2s) or one of the (3s) levels. Thus, the Ne (2s) or (3s) levels are essentially generated at the same rates as those of the He metastables; which happen to be particularly large.

The above processes automatically take place in a simple discharge tube containing the He-Ne mixture. The discharge may be excited by means of a radio frequency or D. C. power. The maser transitions between the s-p groups of levels are themselves grouped into three sets of transitions. The $(2p) \leftarrow (2s)$ transitions fall in the near infrared. In this group, the 1.15μ transition is the most intense one. Because of the particular ease with which this transition may be made to oscillate, most of the frequency stability and precision measurements discussed below are done in the author's laboratory using this particular transition. In fact, a few centimeters of the discharge length is sufficient to yield stable maser oscillation. This may be excited by about half a watt of input radio frequency power. Such a low input power is very essential in minimizing some of the practical difficulties involving thermal changes of the length of the maser interferometer.

The transitions originating from the (3s) to the (2p) group of levels are responsible for a number of optical maser oscillations in the Red-Yellow range of the spectrum. In this group of transitions, the one at 6328Å is the more important one. This transition, being in the visible range, may be used readily for visual study of the character of the output beam.

The (3p) $\leftarrow$ (3s) maser transitions fall in the range of 3μ. The more important one is at 3.39μ. This transition presents a rather large gain factor. In fact, a gain factor as high as 10^4 per meter has been reported for this transition.

Other Gaseous Discharge Systems

For the benefit of chemists, another gaseous discharge system will be described below in which dissociation of an oxygen molecule, O_2, is used for the purpose of producing an oxygen atom in a given excited electronic state. (9), (10). Consider the energy potential curves of O_2 molecule given in Fig. 3. The dissociation limit of the lowest electronic state of the oxygen molecule, $^3\Sigma_g^-$, consists of two atomic oxygen in the ground electronic state, O ($2\ ^3P$). In contrast to this molecular state which is bound and stable, consider now an unstable excited electronic state of O_2 corresponding to a dissociation limit in which one oxygen atom is in an excited state while the other may be in the ground state. The dotted curve in Fig. 3 represents the energy potential curve of such an excited state. This particular state is unstable against dissociation into one oxygen atom in the ($3\ ^3P$) state and the other in the ground ($2\ ^3P$) state.

Let us now consider a gaseous discharge consisting of a few mm Hg of Ne and a few micron partial pressure of O_2 molecules. The lowest excited states of Ne consist of four closely spaced levels. At a pressure of a few mm Hg, all of these four states are long lived and metastables. The energies of these states are designated in the ordinate of Fig. 3. Note that the excitation energies of these states are sufficiently large so that a neon atom in anyone of these states can react with an oxygen molecule and excited it into the unstable electronic state discussed above. Once such an excitation takes place, the oxygen molecule will then fly apart and produces an atomic oxygen in the $(3\,^3P)$ state. In other words, a collision between an oxygen molecule and a neon metastable leads to a dissociative transfer of excitation in which the neon atom emerges in its ground state while the O_2 molecule is dissociated into one atomic oxygen in the O $(3\,^3P)$ and one atomic oxygen in the O $(2\,^3P)$ state.

The above mode of selective production of atomic oxygen in the $(3\,^3P)$ state leads to population inversion between the $(3\,^3P)$ and $(3\,^3S)$ states of oxygen; the $(3\,^3S)$ having an energy which is lower than that of the $3\,^3P$ by about 1.6 volts, (see Fig. 3). Furthermore, the radiative lifetime of the $(3\,^3S)$ is considerably shorter than that of the $(3\,^3P)$ state.

The center frequency of the above transition, $(3\,^3S) \leftarrow (3\,^3P)$, corresponds to a wavelength of 8446 Å. Thus, a discharge tube containing a mixture of Ne and O_2, as described in the above, constitutes an amplifier at 8446 Å.

Within the recent years, inversion of populations within atomic or molecular levels have been observed in a large number of gaseous discharge systems.

In many of these cases, details of the physical processes leading to excitation of given levels, are not known. In cases where the gain per unit length of the tube is not large, a long discharge tube is generally used for achieving maser oscillation. These maser systems are important in that they provide a fairly wide range of frequencies over which coherent optical frequency oscillations may be obtained. In practice, however, there exists a variety of applications in which the operating frequency may be chosen arbitrarily within a given range of wavelengths. In these cases, the discharge systems which provide the necessary amplification of light with the most ease and convenience, are generally most useful.

Excitation of an Optical Resonator

In a gaseous discharge, the radiating atoms are subject to random thermal motions. This effect gives rise to Doppler broadening of the normal spontaneous emission spectra of the atoms. If the center frequency of a given transition is ν_o, the corresponding Doppler width, $\Delta\nu_d$, is given by:

$$\Delta\nu_d = \nu_o \frac{\bar{v}}{c} ,$$

where $\bar{v}$ is the average thermal velocity of atoms and c is the velocity of light. A transition originating from levels which exhibit an inverted population, amplifies an incident light at frequencies within the Doppler width of the corresponding transition. In other words, in the absence of positive feedback to be discussed below, the band pass of an amplifier consisting of the gaseous discharge tube alone, is determined by the Doppler response of the amplifying transition. In the case of the 1.15μ transition of Ne, the Doppler width, $\Delta\nu_d$ is about 900 Mc/sec. and is centered at a frequency of about 2.6×10^{14} cycles/sec.

Let us now consider our optical frequency oscillator which consists of a gaseous discharge tube placed within an optical resonator. The resonator consists of two plane parallel (or two spherical) mirrors which are held rigidly by means of an external mechanical support. Such a configuration forms a Fabry-Perot interferometer. As it was pointed out earlier, an oscillation will result once the gain of the amplifying medium exceeds the reflection loss of power at the end mirrors. The actual oscillation is automatically triggered by the same effect which gives rise to spontaneous emission of photons by atoms. The initial spontaneously emitted photons are then reflected back and forth between the two mirrors and are amplified catastrophically.

The coupling ~~the~~ of the electromagnetic field to the outside world is generally accomplished by allowing a small amount of transmission through the end mirrors. In practice, a diellectrically coated mirror may be designed so that it provides about 99% reflection coefficient corresponding to one per cent reflection loss. Out of the total amount of one per cent reflection loss, about two-thirds of it may be made to pass through the mirror and be transmitted to the outside world and the rest of it is generally lost due to scattering and other dissipative effects. Thus, upon multiple reflections between the two mirrors, a large portion of the power gain may be coupled to the outside world in the form of the output power.

Once the oscillation starts, the amplitude of the electromagnetic field builds up until the point where the rate of stimulated emission of photons by atoms equals the total loss of power. Once this balance of power is satisfied, the steady state oscillation is reached.

In order to describe the frequency of oscillation, we need to know the frequency characteristics of the optical resonator. In the first place, the oscillation frequency occurs within the band width of the amplifying atomic transition which is determined by Doppler effect. Furthermore, its exact wavelength is required to satisfy the boundary conditions imposed by the end mirrors. These boundary conditions define a set of wavelengths at which the interferometer resonates. For this, let us first consider an empty interferometer. The interferometer resonances are given by the condition:

$$L = n \frac{\lambda_n}{2} ,$$

where L is the distance between the two mirrors, n is an integer which defines the order of resonance and λ_n is the wavelength of the corresponding resonance. Let us write this in terms of frequency. Since $\nu = c/\lambda$, we obtain:

$$\nu_n = n \frac{c}{2L}$$

The frequency separations between two successive resonances are given by:

$$\nu_{n+1} - \nu_n = \frac{c}{2L} .$$

In practice, L may be 50 cm. This corresponds to $(c/2L) = 300$ Mc/sec. Thus, the resonances of a 50 cm. interferometer occur every 300 Mc/sec.

For the purpose of our discussions, we also need the frequency width of the response of the interferometer. This width is determined by the ringing time of the resonator, τ, which describes the mean time of decay of an electromagnetic excitation inside the empty resonator. This time is given by:

$$\tau = \frac{L}{c\,(1 - r)}$$

where L is the length of the interferometer, c is the velocity of light and r is the reflection coefficient of the end mirrors. Note that (L/c) is the time during which a light wave travels from one end of the interferometer to the other end. The ringing time, τ, is larger than L/c due to multiple reflections between the two mirrors. This time becomes longer if the reflection coefficient of the end mirrors, r, approaches unity.

The widths of the frequency response of the interferometer, $\Delta\nu_c$ is given by:

$$\Delta\nu_c = \frac{1}{2\pi\tau} = \frac{c(1-r)}{2\pi L}$$

For L = 50 cm and r = 0.99, one obtains $\Delta\nu_c \cong 1$ Mc/sec.

The considerations described in the above are summarized in Fig. 4. The amplifier band pass is the same as the Doppler line shape of the atomic resonance. For 1.15μ transition of Ne, this band pass has a ~~widths~~ width of about 900 Mc/sec. A 50 cm resonator, resonates every 300 Mc/sec. Thus, for the case considered here, at least one interferometer resonance is always present within the width of the atomic transition. Lastly, the width of the interferometer resonance, $\Delta\nu_c$, is about 1 Mc/sec. which is much narrower than the width of the atomic resonance.

According to the above discussions, the interferometer resonances which lie within the width of the atomic transitions are capable of supporting the frequencies at which oscillations may take place. In fact, if the gain of the amplifying medium is large, oscillations may occur simultaneously at several adjacent resonances of the interferometer. Such a situation is generally referred to as multimode excitation of the interferometer.

In practice, the number of simultaneously oscillating modes may be reduced simply by decreasing the discharge intensity so that sufficient gain exists only within a narrow frequency range close to the peak frequency of the atomic resonance. In this case, one may achieve oscillation at only one frequency determined by the one interferometer resonance which happens to be closest to the peak frequency of the atomic resonance.

Once an oscillation sets in at any of the interferometer modes, an extremely pure and monochromatic oscillating optical field will result. This is the topic of our discussions in the following sections.

Let us now consider an interferometer consisting of two plane parallel mirrors. The direction of propagation of light corresponding to normal modes of the interferometer is perpendicular to the end mirrors. In this case, the output beam is parallel and highly directional. The angular spread of the beam is determined by the diffraction effect arising from finite size of the apperture of the beam. If the diameter of the output beam is D, this angualr spread is given by $\theta \cong \lambda/D$. It should be noted that with the aid of an external auxiliary optical system such as a telescope used backwards, the actual diameter of the beam may be magnified. In this case, the angular spread of the final beam is still given by $\theta = \lambda/D$, where D is the magnified aperture of the beam at the output of the telescope. The situation in this case is quite analogous to that of directional microwave sources, where, for instance, by appropriately arranging an array of antennae, the directionality of the beam may be improved.

The gaseous optical masers used in practice, may be divided into two different types. The first type is the well known external mirror masers which are also known as Brewster angle masers.[11] In this type of maser, the mirrors are placed external to the discharge tube and are held rigidly by means of simple mechanical supports. The discharge tube is terminated by two fairly high quality optical windows and the tube is placed within the resonator. (See Fig. (5)). In order to prevent reflection of the light from the end windows of the tube, the two windows are generally held at the Brewster angle, (see Fig. (6)). This is an angle at which an incident wave with a polarization corresponding to E - field in the plane of incident, is transmitted through the end windows without suffering reflections. The structural design of this type of maser is rather simple, (see Fig. (7). It may be built with only a moderate amount of effort. It can provide a highly coherent beam of light with a fair amount of frequency stability and as such, it may be applied to a number of practical problems. However, the ultimate frequency stability obtainable from such a maser suffers from the fact that the interferometer is intercepted by the two end windows of the discharge tube. Slight tilt or distortion of these windows, which may arise due to thermal or microphonic effects, may introduce certain amounts of frequency shift. These particular difficulties are entirely eliminated in the maser designs discussed below.

The other type of maser design may be called the internal mirror maser. In this design the mirrors are placed inside the vacuum system which contains the He-Ne mixture.[(4)] Fig. (8) gives a schematic of the design. The discharge tube is terminated to two end metallic chambers which are held together externally by means of highly rigid mechanical supports. The discharge tube, which is generally made of quartz, is decoupled mechanically from the end chambers through flexible bellows. The mirrors are held rigidly inside the two end chambers. Two windows are provided at the extreme ends of the device to allow coupling of the output power to the outside. This variety of masers are used at the authors laboratory in connection with experiments which require extreme frequency stability of the output beam. Fig. (9) is a photograph of one of these masers.

The Frequency Characteristics

It was pointed out in the above that the oscillation frequency of an optical maser lies within the width of an interferometer resonance. Referring to Fig. (4), this width may be of the order of about one Mc/sec. The actual width of the oscillating optical field, however, is by far narrower than the width of the interferometer resonance. This behavior is essentially the same as that which occurs in any classical regenerative oscillator. For instance, in an ordinary audio frequency or radio frequency oscillator, the widths of the oscillation frequency is by far narrower than the width of the tank circuit which forms the resonating element of the oscillator. It should not hurt if, at this point, I be permitted to speak in electrical engineering terms. The theoretical limit of the frequency spread of an ideal oscillator at low frequencies is determined by the thermal noise giving rise to voltage fluctuations at the grid of the oscillator tube. In fact, these fluctuations are responsible for triggering the oscillator into oscillation. In this respect, a regenerative oscillator may be treated as a regenerative noise amplifier in which an extremely narrow range of the thermal noise is amplified by an enormous amount leading to the actual steady state power output of the oscillator. (This gain is simply the power output, P, divided by $K\,T\Delta\nu_c$ where K is the Boltzman constant, T is temperature and $\Delta\nu_c$ is the band width of the resonating element; the quantity $K\,T\Delta\nu_c$ being the thermal noise power input. This ratio is generally an enormously large number. Thus, by treating an oscillator as a regenerative noise amplifier, we only need to estimate its band width under steady state oscillation conditions, in order to obtain the actual width of oscillation. As a regenerative amplifier, however, we should note that the product of integrated power gain and the band width is nearly a constant. Before the regeneration sets in, roughly speaking, the band width is $\Delta\nu_c$ and the gain may be of the order of unity. Thus allowing for constancy of gain band width product, in the steady state oscillation, we obtain:

$$\Delta\nu \cong \left(\frac{K\,T\Delta\nu_c}{P}\right)\Delta\nu_c$$

$$= \frac{K\,T}{P}(\Delta\nu_c)^2$$

In this equation, $\Delta\nu$ is the spread of the oscillation frequency, P is the power output of the oscillator, $K T \Delta \nu_c$ is the noise power input as discussed above with $\Delta \nu_c$ as the band width of the resonating element. Note that, $\Delta \nu$ is an extremely small fraction of $\Delta \nu_c$. The calculations as outlined above, are of course, intended as only an order of magnitude estimate. It so happens that, allowing for various details such as saturation effects and etc, the final answer is not much different than the one given above.

An optical maser may also be treated as a regenerative noise amplifier. Except, at optical frequencies, the thermal noise is not the important source of random fluctuation of electromagnetic fields. Instead, the zero point quantum fluctuation of the field is the main source of noise which triggers the amplifier into oscillation. The width of the oscillation frequency may be obtained as in the previous case, except k T should be substituted by $h \nu$ where h is the Plank's constant and ν is the oscillation frequency. Thus, in an ideal optical maser in which all of the non-fundamental sources of frequency fluctuations are absent, the limiting spread of oscillation frequency is of the order of:(3)

$$\Delta\nu = \frac{h \nu}{P} (\Delta \nu_c)^2$$

This width is purely quantum mechanical in nature. The zero point quantum fluctuations of the field is actually the same effect, which is responsible for spontaneous emission of an atom in free space. Its manifestation in an optical maser appears in the form of the output power.

The above discussions refer to an ideal optical frequency oscillator. Notice that in a He-Ne maser, P may be about a few milliwatt. For $\Delta \nu_c$ of about one

Mc/sec., we obtain $\Delta\nu \cong 10^{-4}$ cycles/sec. which is extremely small. This is, of course, a fundamental limit. In practice, there exists other sources which result in random frequency fluctuations. The most important is the fact that the frequency of an interferometer resonance is inversely proportional to the length of the optical resonator as discussed earlier. Thus, slow fluctuations of the ~~of the~~ interferometer length appears in the form of frequency fluctuations of the output of the oscillator. The most basic source of such a fluctuation originates from vibrations of normal accoustical mode of the material on which the end mirrors are supported.(5) Even under the most quiet surroundings, these vibrations are excited by thermal partition noise in each accoustical mode. Consider the interferometer spacer to consist of a cylinder of length L and volume V. The lowest accoustical mode corresponds to a wave length equal to 2 L. This mode suffers the largest amplitude of oscillation due to thermal noise. Considering that, at a temperature T, the thermal energy in each mode is k T, the corresponding amplitude of accoustical oscillation, ΔL, in the lowest mode is then given by:

$$\frac{\Delta L}{L} = \sqrt{\frac{k\,T}{Y\,V}}\,,$$

where Y is the Young modulus of our interferometer spacer. Noting the proportionality of the oscillation frequency and the length, we obtain, therefore:

$$\frac{\Delta \nu}{\nu} = \sqrt{\frac{K\,T}{Y\,V}}\,.$$

For the internal mirror masers used at author's laboratories at M.I.T., the above quantity, estimated at room temperature, is $\frac{\Delta\nu}{\nu} = 10^{-14}$.

In order to approach the above limit experimentally, the spureous sources of random accoustical modulations such as those caused by microphonics and thermal drifts, should be minimized. So far, under highly isolated accoustical and thermal conditions, we have been able to obtain at M. I. T. at frequency purity of $\frac{\Delta \nu}{\nu} = 8 \times 10^{-14}$. This result will be discussed further below.

The frequency characteristics of a maser may be measured using a Super Heterodyne technique.(12) Fig. (10) gives the block diagram of electronic systems used for study of the He - Ne masers at M. I. T. The output of two independently oscillating masers are mixed on the photocathode of a photomultiplier. The length of each maser is adjusted so that they each oscillate at a slightly different frequency. Since the photo current of a phototube is proportional to the square of the amplitude of the electromagnetic field incident on its photocathode, the output of the photomultiplier will contain an oscillatory component at the difference frequency of the two incident fields. In practice, the output of the phototube is fed into a radio frequency (or audio frequency) receiver and is subsequently detected using standard radio frequency receivers. (See Fig. (9)). If the beat note is adjusted to fall within the audio frequency, it can be fed into a loudspeaker. In this case, one is then able to hear a fairly clear whistle resulting from the beat frequency. ~~Fig. (10) gives an oscilloscope display of a beat note at about one kc/sec~~. Study of the frequency purity of the beat note gives the details of the frequency purity of the output of the two masers.

In our experiments at M. I. T., the frequency drift due to slow changes of ambient temperature has been reduced to about one part in 10^{13} per second.(5) This result was obtained for free running masers without the use of any automatic feedback for control of parameters such as temperature. It should be pointed out that, in practice, a massive interferometer responds slowly to changes of ambient temperature. In the actual experiments, the masers were placed inside an isolated vault located in the basement of a castle which is built on a solid rock on the M. I. T. campus at Round Hill, near New Bedford. This locality happens to be fairly removed from heavy industry which is generally a major source of man made accoustical noise and microphonic disturbances. Furthermore, the masers used were of the internal minor type, discussed above. In the design of the masers, considerable care was taken to achieve a high degree of structural rigidity. Fig. (11) gives a photograph of one of these He-Ne masers. The discharge was excited by means of a highly stable radio frequency oscillator. The power input to the tube was less than five hundred milliwatt. The discharge glow was rather mild and extended only over a length of the order of about a few cm. This mode of operation was possible because of a high degree of ease with which the 1.15μ transition may be generally made to oscillate in the He-Ne mixture. In the actual experiment, the masers were allowed a warm-up period of many hours. The measurements were done from the outside of the vault by means of remote controls.

Under normal laboratory conditions, a well designed internal mirror maser with sufficient care is capable of producing a frequency stability of about one part in 10^{10}. It should be pointed out, however, that in many applications a high degree of frequency stability such as those described in the above, is not necessary. In these cases, a simple external mirror maser may be used without the necessity of exercising cares of the kind needed for ultimate frequency stability.

Detection of Small Changes of Length

We have seen in the above that, under quiet laboratory conditions, a He - Ne maser can readily provide a frequency purity better than one part in 10^{13}. This immediately implies that the spureous changes of the lengths of the maser interferometer may be reduced below one part in 10^{13}. The actual change of length, ΔL, corresponding to this degree of stability is:

$$\Delta L = 10^{-13} L$$

For the masers used at M.I.T., L is 50 cm. Thus, our limiting change of length has been $\Delta L = 5 \times 10^{-12}$ cm. In Angstrom unit, this is, $\Delta L = 5 \times 10^{-4}$ Å. Notice that one Angstrom unit is about the size of a single atom. A nucleus of an atom is about 10^{-3} Å. Thus, we are able to detect changes in length to within a range of the order of a nuclear radius. It should also be pointed out that the length L is defined as an effective distance between the surfaces of the two end mirrors. These surfaces are defined in terms of averages over rapid zero point vibrations of atoms around their equilibrium positions.

To capitalize on such extreme sensitivity in detection of small changes in length, we have performed an experiment which is essentially a high precision version of Michelson and Morley experiment.(13) For this purpose, the two He - Ne masers were mounted perpendicular to each other on a rotable platform. The beat frequency between the two masers were observed while the platform was set in oscillatory motion around a vertical axis perpendicular to its plane. The observations on the beat note were done using electronic scheme discussed in the above. ~~(See also Fig (10).~~ This experiment may be described as an ether drift experiment or a test in establishing an upper limit to isotropy of space. In our preliminary experimental measurements, we have been able to show to within an accuracy of one part in 10^{11}, the absence of a frequency shift and hence, the absence of a fundamental change in length.

(5)

as a function of orientation in space. This verifies the presence of Lorentz-Fitzgerald contraction term in the space-time transformation to within one part in a thousand of $\frac{v^2}{c^2}$, where v is the orbital velocity of the motion of earth around the sun and c is the velocity of light. This measurement is better than previous determinations by a factor of about three. This experiment is at the present under further progress.

It should be noted that a frequency stability of one part in 10^{13} implies the possibility of using the output of a He - Ne maser for the purpose of obtaining interference fringes over very long distances which, in principle, may be of the order of many miles. Under laboratory conditions, a long distance interfermetry over distances of many meters may be done in a vaccum. This is expected to be used in the future as a means for accurate comparison of wavelengths and distances.

Frequency Reproducibility and Lengths Standard

The accuracy with which the wavelength of the output of a gaseous maser may be used as a standard of length depends on the extent to which a fixed frequency may be defined within the line width of the corresponding atomic resonance. In other words, our ability to reproduce the same frequency in two different masers determines the limit of accuracy in the use of the device as a length standard. One way of doing this is to prescribe a procedure according to which the oscillation frequency may be reset close to the peak frequency of the atomic resonance. The following discussions are concerned with this problem.

It was pointed out earlier in our discussions that a gaseous optical maser may be made to oscillate readily at a single frequency. For this, the discharge intensity is adjusted so that sufficient gain exists only within a narrow frequency range around the peak frequency of the Doppler broadened atomic transition. In this case, the oscillation frequency takes place only on the one interferometer resonance which happens to be closest in frequency to the center frequency of the atomic transition. The actual frequency of oscillation, however, depends on the exact length of the interferometer. Thus, by adjusting the length of the interferometer, the oscillation frequency may be tuned within a narrow frequency range around the peak frequency of the atomic transition. In this case, the power output depends critically on the exact magnitude of the detuning of the oscillation frequency from the center frequency of the atomic resonance. Furthermore, this dependence shows a symmetrical behavior with respect to the peak frequency of the atomic response if the latter is itself symmetrical. In this case, the symmetrical response of the power output versus the oscillation frequency may be used for resetting the oscillation frequency close to the center frequency of the atomic transition. This may be accomplished, for instance, by observing the power output while the interferometer length is changed slowly. Once the symmetrical response of the power output versus the interferometer length is observed in detail, its center may be reproduced by merely resetting the length of the interferometer to the appropriate corresponding operating point.

In a gaseous maser operating close to the oscillation threshold, the peak frequency of the atomic transition does not correspond to the maximum power output. Instead a power dip occurs close to the peak frequency. (14), (15) Fig (12) gives an experimental tracing which represents the power output versus the oscillation frequency of a He - Ne maser. This tracing was obtained with ~~the~~ a He - Ne maser oscillating in a single mode at the 1.15μ transition. The Ne sample used in the maser was isotropically enriched in Ne^{20}. The ordinary Ne sample consists of about 92 per cent Ne^{20} and 8 per cent Ne^{22}. Due to isotope shift, the center frequency of the 1.15μ transition differs slightly for the two isotopes. (14) As a result in an ordinary Ne sample, the normal spontaneous emission line shape of the 1.15 transition is slightly distorted and asymmetrical.(14) However, by using an isotropically enriched sample of Ne, a high degree of symmetry is stored in the line shape. This results in a symmetrical behavior of the power output versus the oscillation frequency(14) as is evident from Fig. (12)

The reason for the presence of the power dip of Fig ( ) lies in the saturation behavior of the atomic transition. As it was pointed out earlier, an oscillation will result if the initial single pass gain of the amplifying medium exceeds the loss of power at the end mirrors. Due to saturation effect, the gain of the amplifying medium decreases as the amplitude of the oscillating field builds up within the optical resonator. The steady state oscillation corresponds to the value of the optical frequency field for which the gain of the amplifying medium equals the loss of optical power at the end mirrors. (The saturation effect arise due to rapid induced transitions between the two maser levels which tends to equalize the populations of the two levels.) Inside the optical resonator, the atoms are subjected to an optical frequency field which is in the form of a standing wave. It can be shown that, in this case, a Doppler broadened atomic resonance saturates more readily at the peak frequency of the atomic resonance then at frequencies on either side of the resonance. Thus, in spite of the fact that the unsaturated gain is less at a frequency detuned from the line center, the steady state power output is somewhat larger than its value at the line center, as is evident from Fig (12) It should be pointed out that this effect by itself is an interesting one, in that, it depends on details of atomic collisions as well as the details of interaction of atoms with an intense optical frequency field. The exact shape of the power response as given in Fig (12) has already provided considerable information on the saturation behavior of the excited states of Ne atoms.

Using the prescription described in the above, the frequency of a given He - Ne maser may be reset, to a high degree of accuracy, close to the center of the Ne resonance. This by itself, however, is not sufficient for the purposes of length standard. For this, it should be noted that, under our experimental conditions, the center frequency of an atomic resonance is not quite an invariant quantity. For instance the line shape of an atomic resonance, and thus its line center, shows a slight dependence on the exact pressure of the gas. As a result, if the gas pressure in two different masers are not quite the same, the reset frequencies of the two masers may differ slightly. The pressure effects are at the present subject to extensive studies at the author's laboratories at M.I.T.

At the present, experimentally, using a technique similar to the one described in the above, a frequency reproducibility to within one part in 10^9 at the 1.15μ transition of Ne has been obtained.(5) It should be pointed out that a frequency reproducibility to one part in 10^8 may readily be obtained with only a fair amount of efforts. Considering that the high degree of coherence of the maser beam makes it possible to obtain interference fringes over long distances, a frequency reproducibility to within one part in 10^8 by itself makes the device a highly useful candidate as a length standard.

In addition to spectroscopic applications of the device, there exist a number of practical applications worth noting. The high intensity together with high degrees of coherence of the output of a continuously operating He - Ne maser is being used nowadays for improved quality controls in constructions and tests of precision optical components. The directionality of the output beam and its high degree of coherence makes it an attractive candidate for a future use as a long distance communication channel. The extreme sensitivity of the device in detection of minute changes in length, as described in the above, has attractive possibilities in applications to the art of seismology.

At the close of this talk, one should be reminded that some of the future practical as well as scientific applications of the device still await further technological developments.

*Supported by NASA Grant NsG-330

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FIGURE CAPTIONS

Fig. (1) Stimulated emission of radiation leads to amplification of an input wave if the population of upper energy level, N_2, is larger than that of the lower level, N_1.

Fig. (2) Energy level diagram of some of the excited states of He and Ne. The Paschen notation is used for designation of Ne levels. The electron configuration corresponding to 1s, 2s, and 3s group of levels are respectively $(2p_5)$ 3s, $(2p_5)$ 4s and $(2p_5)$ 5s and those corresponding to 2p and 3p group of levels are $(2p_5)$ 3p and $(2p_5)$ 4p.

Fig. (3) Potential energy curve of O_2.

Fig. (4) The Doppler line shape of the Ne is 900 Mc/sec. wide centered at 2.6×10^{14} cycles/sec. For 50 cm mirror spacing, the interferometer resonances appear every 300 Mc/sec. The width of each interferometer resonance is about one Mc/sec.

Fig. (5) Schematics of an external mirror maser.

Fig. (6) Photograph of the end window of a Brewster angle discharge tube.

Fig. (7) Photograph of a Brewster angle maser.

Fig. (8) Schematics of an internal mirror maser.

Fig. (9) Photograph of a rigid external mirror maser.

Fig. (10) Block diagram of the Super Heterodyne arrangement for observation of beat note between the output of two He-Ne masers.

~~Fig. (11) Oscilloscope display of the optical beat note at audio frequency.~~

FIGURE CAPTIONS, Cont.

Fig. 11 (~~12~~) An internal mirror maser. Four Quartz Rods are used for the support of the end chambers containing the mirrors.

Fig. 12 (~~13~~) Experimental tracing of the power output versus the oscillation frequency of a He-Ne maser oscillating in a single mode.

Fig 1

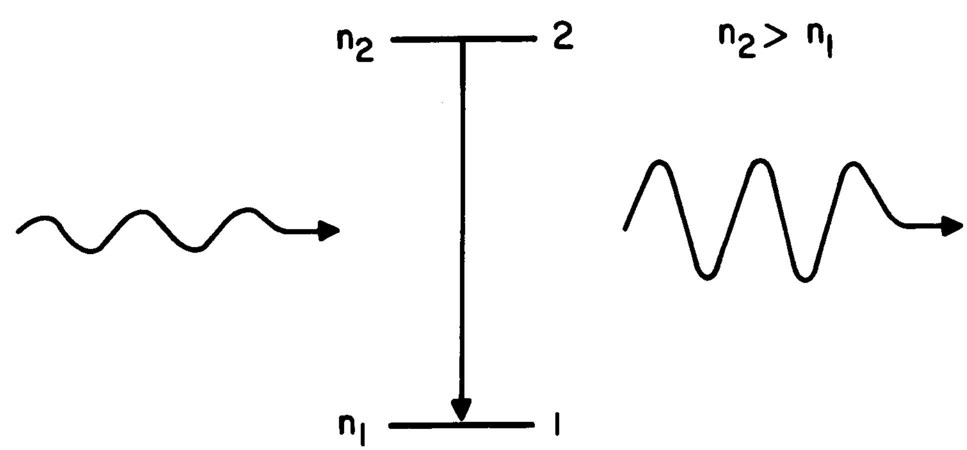
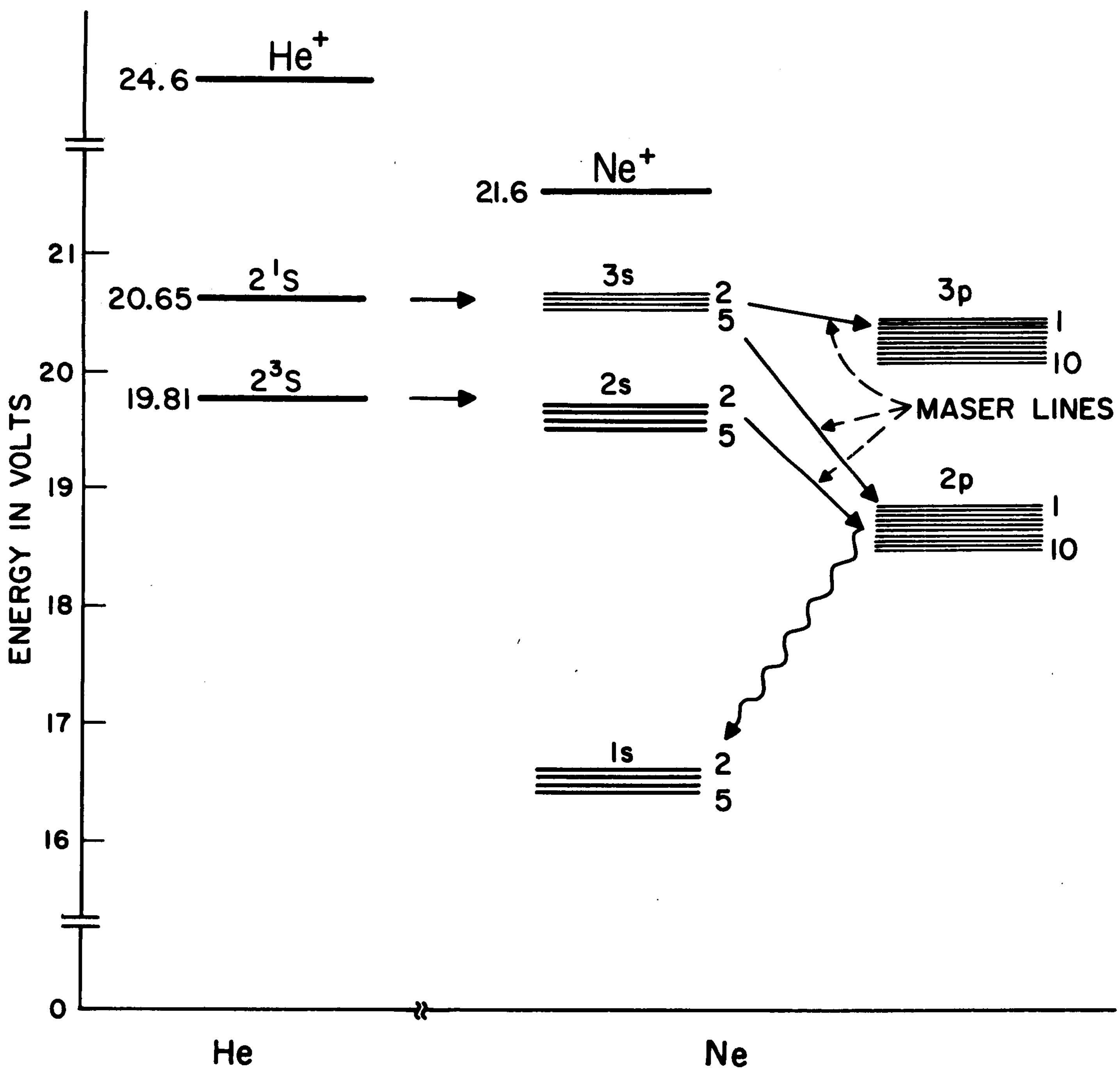
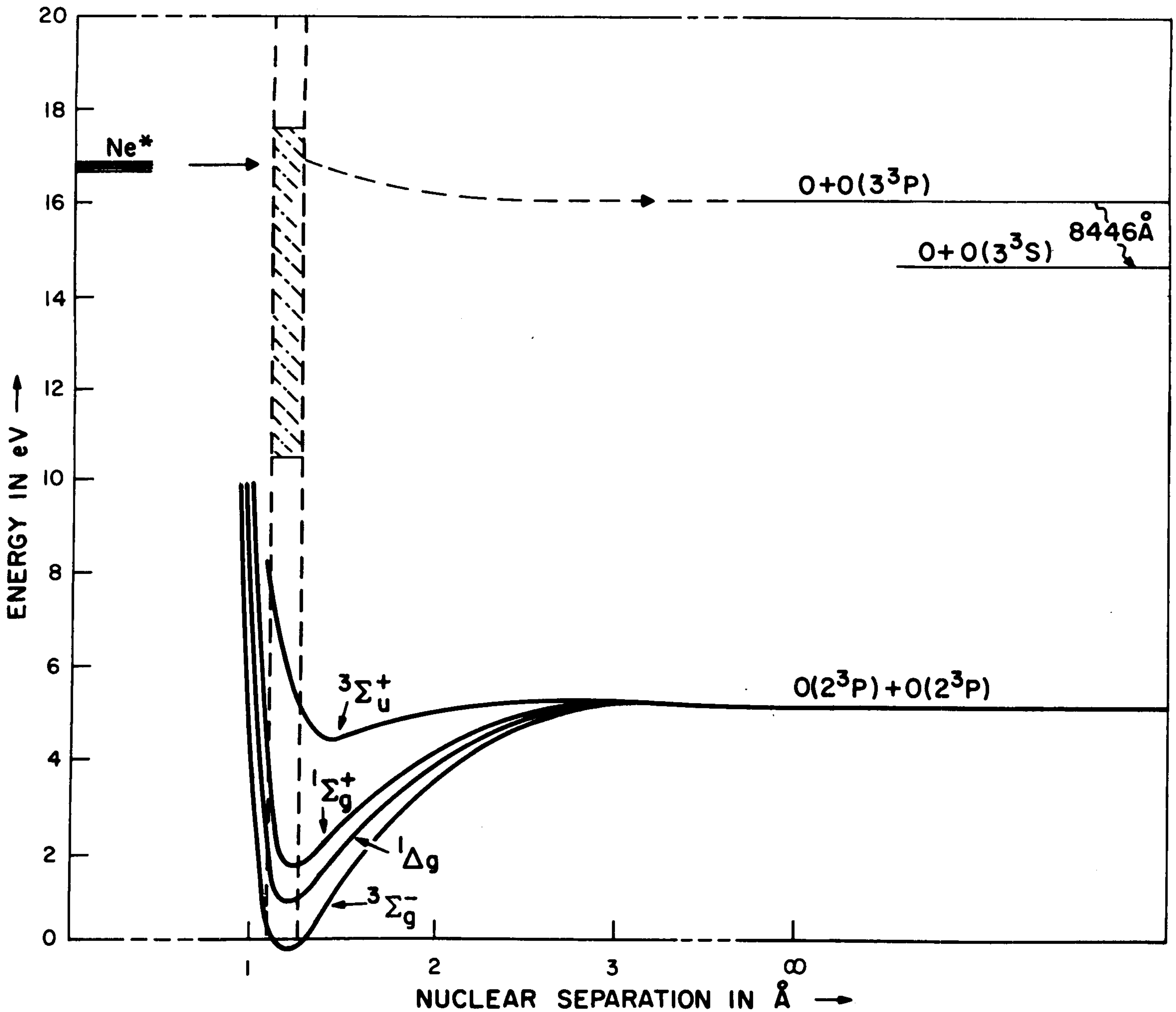


Fig 2

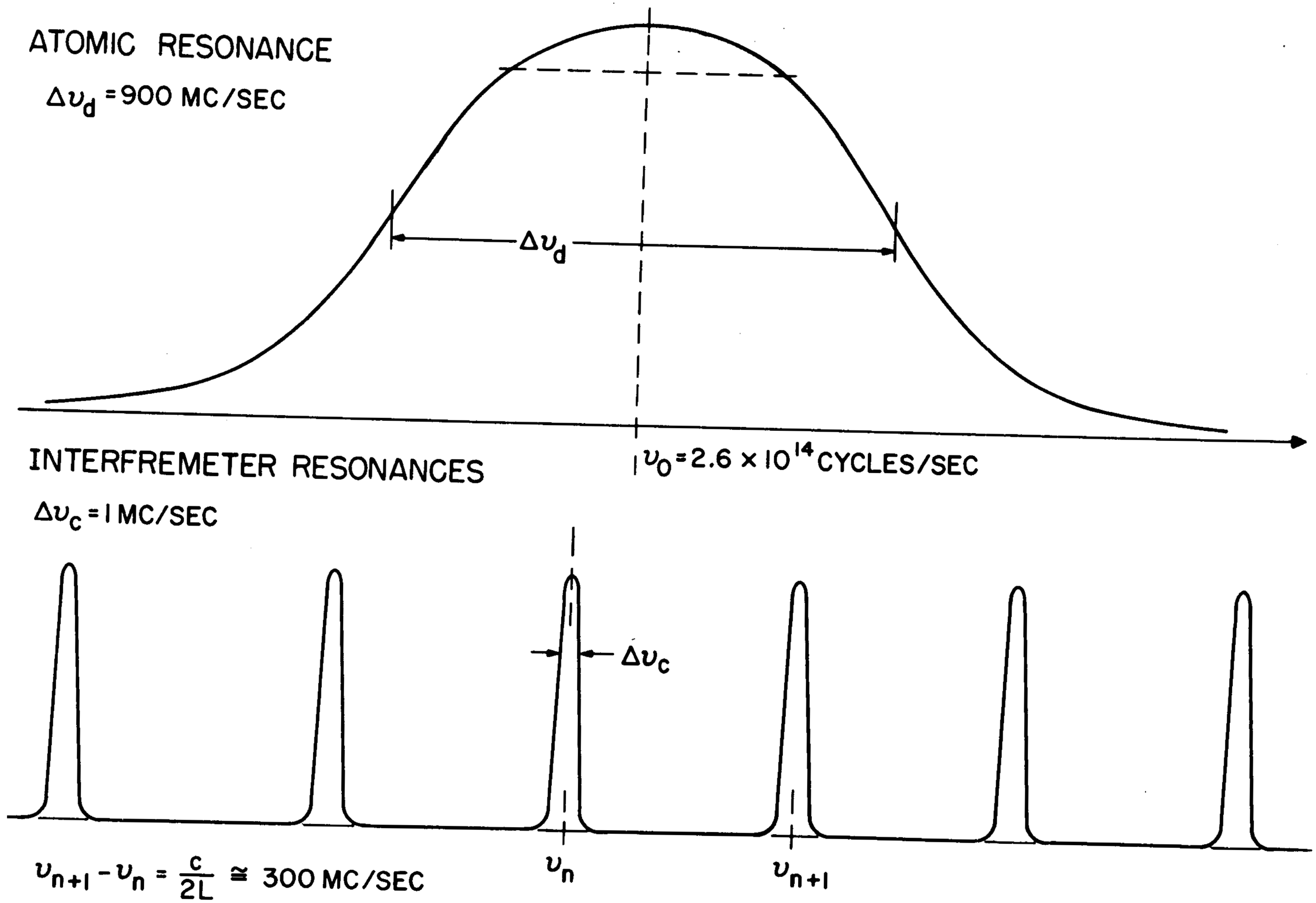


ENERGY IN VOLTS
24.6
He+
21.6
Ne+
21
20.65
2 1S
3s
2
5
3p
1
10
20
19.81
2 3S
2s
2
5
MASER LINES
19
2p
1
10
18
17
1s
2
5
16
0
He
Ne

Fig 3

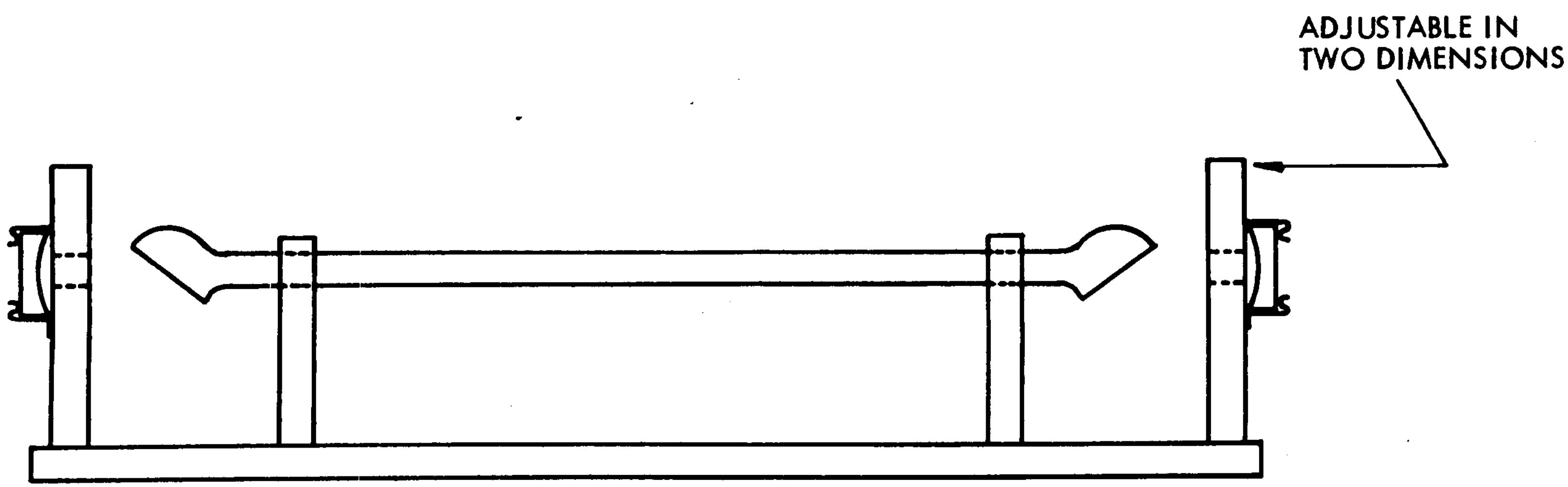


20
18
16
14
12
10
8
6
4
2
0
ENERGY IN eV →
Ne*
0+0(3³P)
0+0(3³S)
8446Å
0(2³P)+0(2³P)
$^3\Sigma_u^+$
$^1\Sigma_g^+$
$^1\Delta_g$
$^3\Sigma_g^-$
1
2
3
∞
NUCLEAR SEPARATION IN Å →

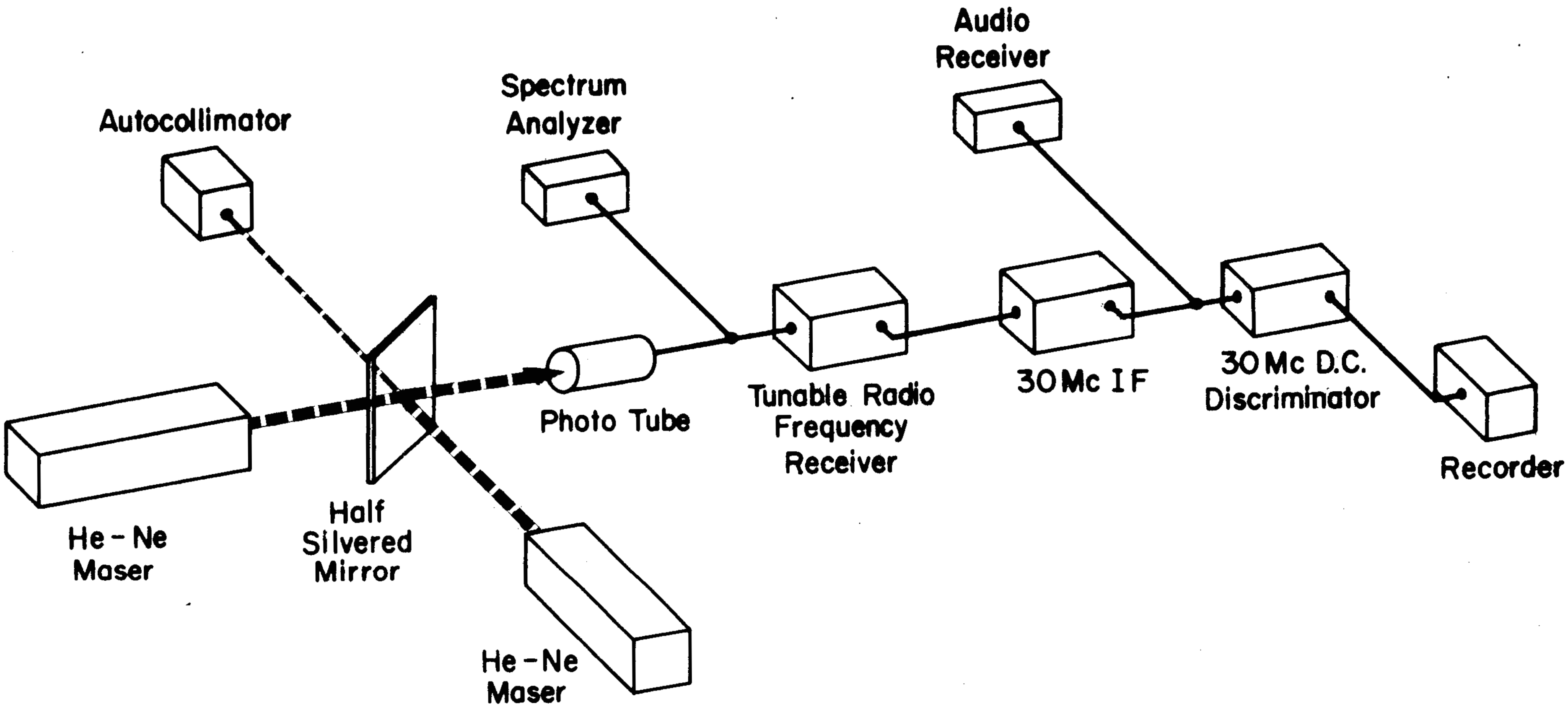


ATOMIC RESONANCE
$\Delta\nu_d = 900$ MC/SEC
$\Delta\nu_d$
$\nu_0 = 2.6 \times 10^{14}$ CYCLES/SEC
INTERFREMETER RESONANCES
$\Delta\nu_c = 1$ MC/SEC
$\Delta\nu_c$
ν_n
ν_{n+1}
$\nu_{n+1} - \nu_n = \frac{c}{2L} \cong 300$ MC/SEC

Fig 5



SCHEMATIC OF EXTERNAL MIRROR MASER



OPTICAL SUPER HETERODYNE

[illegible] 12